

A cosmologically motivated description of the dark matter halo profile for the Low Surface Brightness Galaxy, Malin 1

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ABSTRACT

In this paper we derive a possible mass profile for the low surface brightness galaxy, Malin 1, based upon previously published space-based and ground-based photometric properties and kinematics. We use properties of the bulge, normal disk, outer extended disk and H I mass as inputs into mass profile models. We find that the dark matter halo model of Malin 1 is best described by a halo profile that has undergone adiabatic contraction, inconsistent with the findings for most disk galaxies to date, yet consistent with rotation curve studies of M31. More importantly, we find that Malin 1 is baryon dominated in its central regions out to a radius of ~ 10 kpc (in the bulge region). Low-surface brightness galaxies are often referred to as being dark matter dominated at all radii. If this is the case, then Malin 1 would seem to have characteristics similar to those of normal barred disk galaxies, as suggested by other recent work. We also find that Malin 1 also falls on the rotation curve shear versus spiral arm pitch angle relation for normal galaxies, although more LSB galaxies need to be studied to determine if this is typical.

Subject headings: Galaxies

1. Introduction

Malin 1 is a highly unusual disk galaxy characterized by an enormous H I rich and extremely low surface brightness disk (Bothun et al. 1987; Pickering et al. 1997). It has the largest radial extent of any known spiral galaxy, with low surface brightness emission extending out to ~ 100 kpc, and its disk was found to have an extrapolated central surface brightness of only $\mu_0 \simeq 25.5$ mag arcsec $^{-2}$ in the V -band (Bothun et al. 1987; Impey & Bothun 1989), with an exponential disk scalelength of $\sim 50 - 70$ kpc (e.g., Moore & Parker 2007). Although it has a very low surface brightness, its optical luminosity is $M_v \simeq -22.9$ mag (Pickering et al. 1997), due to its large extent. It also has an extremely high gas mass, with an estimated H I mass of $\sim 7 \times 10^{10} M_\odot$ (Pickering et al. 1997; Matthews et al. 2001). As a result Malin 1 is often considered a Low Surface Brightness (LSB) galaxy. However, recent studies of Malin 1

have started to highlight features more typical of normal disk galaxies (e.g., Barth 2007). The analysis of a *Hubble Space Telescope* (HST) WFPC2 F814W (I -band) image presented by Barth (2007) shows that Malin 1 possesses an inner normal stellar disk, with characteristics similar to those in regular disk galaxies. They calculate an exponential disk scalelength of ~ 5 kpc and a disk central surface brightness of ~ 20 mag arcsec $^{-2}$. These data suggest that Malin 1 has characteristics similar to those of normal disk galaxies, in particular barred lenticular galaxies (SBOs), which typically show an outer disk with a larger disk scalelength (Aguirre et al. 2005). Moore & Parker (2007) have also recently presented a deep ground-based image of Malin 1, which shows spiral structure in its inner disk, another hint that Malin 1 may be more closely related to normal disk galaxies than originally thought. Indeed, Malin 1 may have much in common with the recently discovered class of ob-

TABLE 1
PROPERTIES OF THE BULGE, INNER AND OUTER DISK AND DARK MATTER HALO OF MALIN 1

Property	Measurement
Bulge effective radius ¹ , R_e	0.6 kpc
Bulge effective surface brightness ¹ , μ_e	16.8 mag arcsec ⁻²
Inner disk scalelength ¹ , h_{in}	4.8 kpc
Inner disk central surface brightness ¹ , I_{in0}	20.1 mag arcsec ⁻²
Outer disk scalelength ² , h_{out}	53 kpc
Outer disk central surface brightness ² , I_{out0}	24.8 mag arcsec ⁻²
H I mass ³ , M_{HI}	$(6.8 \pm 0.7) \times 10^{10} M_\odot$
Spiral arm pitch angle, P	$25^\circ 0 \pm 1^\circ 0$
Halo concentration, c_{vir}	8
Halo virial mass, M_{vir}	$2.6 \times 10^{12} M_\odot$

¹From Barth (2007) who used an HST/WFPC F814W (*I*-band) image of Malin 1 to perform a two-dimensional structural decomposition into bulge and disk components.

²From Moore & Parker (2007) who determine properties of the outer disk from a deep ground-based *R*-band image of Malin 1.

³From Pickering et al. (1997).

jects that host extended ultraviolet (XUV) disks, such as M83 (Thilker et al. 2005) and NGC 4625 (Gil de Paz et al. 2005). All of these objects have apparently normal disks, but are surrounded by very extended low surface brightness emission (sometimes missed entirely in the optical) that shows up in the UV as a result of recent star formation.

In this paper we make use of a recently published H I rotation curve (Sancisi & Fraternali 2007) to determine a possible mass profile for Malin 1. We use the bulge/disk decomposition from Barth (2007) and the properties of the outer disk from Moore & Parker (2007) in our model. We also take into account the H I mass from Pickering et al. (1997). The mass models produced show that Malin 1 is baryon dominated out to a radius of ~ 15 kpc. As LSB galaxies are typically dark matter dominated down to small radii (e.g., de Blok & McGaugh 1997; Kuzio de Naray et al. 2008) on the surface it would appear that LSB may not be typical of LSB galaxies. However, it should be noted that the studies presented by de Blok & McGaugh (1997) and Kuzio de Naray et al. (2006, 2008) consisted of dwarf LSB galaxies, which seem to be dark matter dominated beyond the inner ~ 1 kpc and may be baryon dominated within this radius. By extrapolation to much large giant LSB galaxies, such as Malin 1, it is not implausible that these objects would also be baryon dominated out

to 10–15 kpc. We also find that the rotation curve shear and spiral arm structure of Malin 1 show that it sits nicely on the spiral pitch angle versus shear relation for normal disk galaxies reported by Seigar et al. (2005, 2006). However, we also note that more LSB galaxies need to be studied to determine if they typically fall on the same relation.

2. Data

Throughout this paper we use previously published data to determine characteristics of both the stellar, gaseous and dark matter components. We use the *HST* WFPC2 F814W image described by Barth (2007) and the characteristics of the bulge and inner disk described therein. We also use the deep ground-based *R*-band image from Moore & Parker (2007) to determine the spiral arm pitch angle of Malin 1 and we also use their exponential scalelength of the outer disk of Malin 1 in our description of the baryonic mass profile.

3. Mass modeling of Malin 1

3.1. The baryonic contribution

Our goal is to determine a cosmologically motivated mass model for Malin 1. In order to estimate the baryonic contribution to the rotation curve, we use published bulge, inner (stellar) disk and outer (gas) disk properties. We then deter-

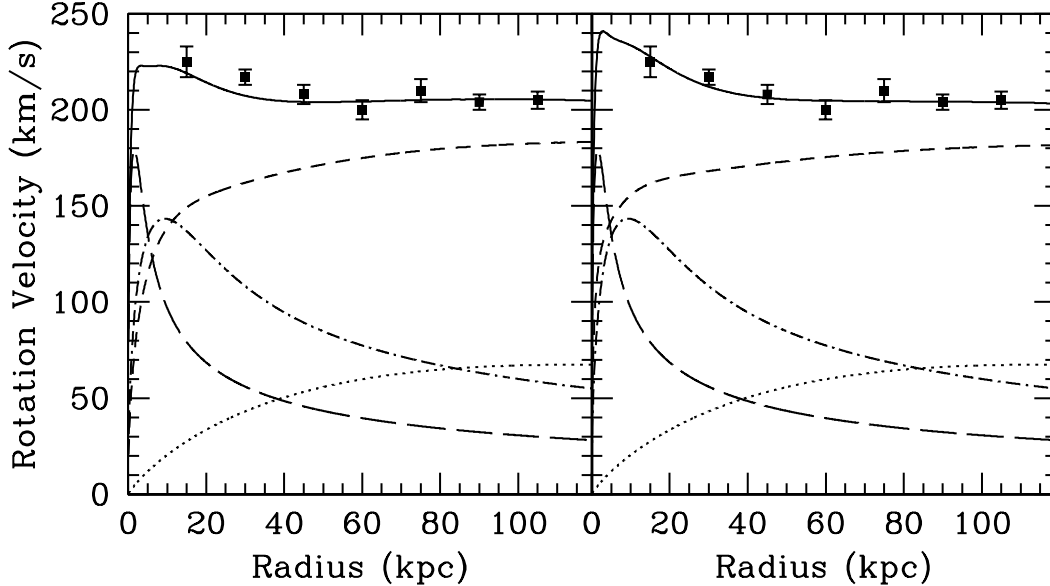


Fig. 1.— H I rotation curve data from Sancisi & Fraternali (2007) with best fitting model rotation curve (solid line) overlaid. Also plotted are the contributions from the bulge (long dashed line), the inner stellar disk (dot-dashed line), the outer H I+stellar disk (dotted line) and the dark matter halo (short-dashed line). *Left panel:* non-AC model; *Right panel:* AC model.

mine several possible mass models and determine the model that best describes the observed H I rotation curve, by minimizing the reduced- χ^2 .

The characteristics of the bulge and inner disk are taken from Barth (2007) who performed a 2-dimensional bulge/disk decomposition of Malin 1, based on an *HST* WFPC2 F814W (*I*-band) image. We then use the characteristics of the outer disk as determined from a deep ground-based *R*-band image presented by Moore & Parker (2007). The characteristics of these components are listed in Table 1.

We then assign masses to the bulge, inner disk and outer disk of Malin 1. In order to do this we have made use of the study of 7 giant LSBs from Sprayberry et al. (1995). Using their data, we determine typical colors for the bulge and disk components for giant LSB galaxies and apply these same colors to the bulge and disk components of Malin 1 (assuming the inner and outer disk have similar colors). We find that a typical bulge color for LSB galaxies is $B - R = 1.5 \pm 0.4$ and a typical disk color is $B - R = 1.2 \pm 0.2$. Based upon these colors we determine a range of calibrated stellar mass-

to-light (M/L) ratios for the *I*-band and *R*-band from Bell et al. (2003) for the bulge, $(M/L_I)_{\text{bulge}}$, the inner disk, $(M/L_I)_{\text{disk}}$, and the outer disk, $(M/L_R)_{\text{disk}}$. In our models we allow mass-to-light ratios in the ranges of $1.5 < (M/L_I)_{\text{bulge}} < 3.8$, $1.2 < (M/L_I)_{\text{disk}} < 2.1$ (measured in *I*-band solar units) and $1.3 < (M/L_R)_{\text{disk}} < 2.7$ (measured in *R*-band solar units), and we allow the mass-to-light ratios to vary in these ranges in steps of 0.1. Large ranges in mass-to-light ratios are used in order to take into account the large scatter in the relationships presented by Bell et al. (2003). We use the bulge, inner disk and outer disk light profiles to determine the stellar mass contribution $M_* = (M/L_I)L_{\text{bulge}} + (M/L_I)L_{\text{in}} + (M/L_R)L_{\text{out}}$, where L_{bulge} is the *I*-band luminosity of the bulge, L_{in} is the *I*-band luminosity of the inner disk and L_{out} is the *R*-band luminosity of the outer extended disk. This outer extended disk was seen in the deep imaging of Moore & Parker (2007) to extend to at least a radius of 124 kpc. This disk is dominated by H I gas and is estimated to have a mass of $(6.8 \pm 0.7) \times 10^{10} M_\odot$ (Pickering et al. 1997). In this paper we also take into account this gas mass of the outer H I disk and assume that it

follows the same exponential disk scalelength of 53 kpc as the low surface brightness R -band disk determined by Moore & Parker (2007). We also add in a stellar component (as described above) based upon the R band surface brightness measurements of Moore & Parker (2007) and the above M/L values. It turns out that the stellar mass and the gas mass in the outer disk are approximately equal.

3.2. Modeling the dark matter halo

We now explore a range of allowed dark matter halo masses and density profiles, adopting two extreme models for disk galaxy formation. In the first we assume that the dark matter halo surrounding Malin 1 has not responded significantly to the formation of a disk, i.e., adiabatic contraction (AC) does not occur. We refer to this as our “non-AC” model. In this case, the dark matter contribution to the rotation curve is described by a density profiles that mirrors those found in dissipationless dark matter simulations,

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \quad (1)$$

where r_s is a characteristic “inner” radius, and ρ_s is a corresponding inner density. Here we have adopted the profile shape of Navarro et al. (1996; hereafter NFW). The NFW profile is a two-parameter function and is completely specified by choosing two independent parameters, e.g., the virial mass M_{vir} (or virial radius R_{vir}) and concentration $c_{\text{vir}} = R_{\text{vir}}/r_s$ define the profile completely (see Bullock et al. 2001b for a discussion). Similarly, given a virial mass M_{vir} and the dark matter circular velocity at any radius, the halo concentration c_{vir} is completely determined.

In the second class of models we adopt the scenario of adiabatic contraction (AC) discussed by Blumenthal et al. (1986; see also Bullock et al. 2001a and Pizagno et al. 2005). Here we assume that the baryons and dark matter initially follow an NFW profile and that the baryons cool and settle into the halo center slowly compared to a typical orbital time. This slow infall provokes an adiabatic contraction in the halo density distribution and gives rise to a more concentrated dark matter profile. The idea of adiabatic contraction was originally discussed as to explain the “conspiracy” between dark halos and disk sizes that gives rise to a featureless rotation curve (Rubin et al.

1985) but has since proven to be remarkably accurate in describing the formation of disk galaxies in numerical simulations (e.g., Gnedin et al. 2004, and references therein), although the degree to which this process operates in the real universe is currently uncertain. For example, Dutton et al. (2005) showed that adiabatic contraction models are inconsistent with the rotation curves measured and the expected NFW concentrations for a sample of six galaxies. They suggest that mechanisms such as stellar feedback and stellar bars may result in less concentrated halos than predicted by adiabatic concentration.

In our AC model we take the contraction into account following the prescription of Blumenthal et al. (1986). Note that Gnedin et al. (2004) advocate a slightly modified prescription, but the differences between the two methods are small compared to the differences between our AC model and our non-AC model. In principle, any observational probe that can distinguish between AC and non-AC-type scenarios provides an important constraint on the nature of gas infall into galaxies (i.e., was it fast or was it slow?).

We iterate over the central and $\pm 1\sigma$ values found in the bulge-disk decompositions for h and L_{disk} and explore the values of mass-to-light ratio discussed above, for the bulge $1.5 < (M/L_I)_{\text{bulge}} < 3.8$ for the inner disk $1.2 < (M/L_I)_{\text{disk}} < 2.1$ and for the outer disk $1.3 < (M/L_R)_{\text{disk}} < 2.7$. In each case we assume average values for $(M/L_I)_{\text{bulge}}$, $(M/L_I)_{\text{disk}}$ and $(M/L_R)_{\text{disk}}$. For each choice of bulge-inner disk-outer disk model parameters and mass-to-light ratios, we allow the (initial) halo NFW concentration parameter to vary over the range of viable values, $c_{\text{vir}} = 3 - 31$ (Bullock et al. 2001b). We then determine the halo virial mass M_{vir} necessary to reproduce the rotation velocity at 2.2 inner disk scalelengths ($V_{2.2_{\text{in}}} = 10.56$ kpc) and the rotation velocity at 2.2 outer disk scalelengths ($V_{2.2_{\text{out}}} = 116.6$ kpc) for the galaxy and determine the implied fraction of the mass in the system in the form of stars compared to that “expected” from the Universal baryon fraction, $f_* = M_*/(f_b M_{\text{vir}})$. We make the (rather loose) demand that f_* lies within the range of plausible values $0.01 f_b < f_* < f_b$.

For each chosen value of c_{vir} and adopted disk formation scenario (AC or non-AC), the chosen

TABLE 2
MALIN 1 BEST FITTING MODELS.

Parameter	non-AC	AC
Shear	0.50 ± 0.01	0.47 ± 0.01
NFW concentration, c_{vir}	15	8
Virial mass, $M_{\text{vir}} (M_{\odot})$	1.8×10^{12}	2.6×10^{12}
Bulge mass-to-light ratio, $(M/L_I)_{\text{bulge}}$	2.2	2.2
Inner disk mass-to-light ratio, $(M/L_I)_{\text{disk}}$	1.2	1.2
Outer disk mass-to-light ratio, $(M/L_R)_{\text{disk}}$	1.3	1.3
χ^2/ν	2.45	1.30

NOTE.—“non-AC” is the best-fit model to the rotation curve from Sancisi & Fraternali (2007) without adiabatic contraction. “AC” is the best-fit model to the same rotation curve data using the Adiabatic Contraction prescription from Blumenthal et al. (1986).

values of $V_{2.2\text{in}}$ and $V_{2.2\text{out}}$ constraints define the rotation curve completely and thus provide an implied shear rate at every radius. Figure 1 shows the H I rotation velocity data from Sancisi & Fraternali (2007) overlaid with best-fitting model rotation curves that we derive for Malin 1 for both the non-AC (*left panel*) and AC (*right panel*) models. The best fit overall rotation curve model is divided into its bulge, inner disk, outer disk and halo components. We find that the best fitting rotation curve model is more consistent with a halo that has undergone adiabatic contraction, rather than a pure NFW model. Our preference for the AC model is inconsistent with the findings that an adiabatically contracted halo model rarely describes the observed rotation curves of disk galaxies (e.g., Kassin et al. 2006a, b), yet consistent with the rotation curve of M31, which also appears to require adiabatic contraction (Klypin et al. 2002; Seigar et al. 2008a). Given the accumulation of evidence that the rotation curves of disk galaxies (especially late-type disk galaxies with little or no bulge) tend to be inconsistent with the predictions of AC, it is surprising that our AC model seems to work best for Malin 1. Considering that the rotation curve of M31 (the nearest and best-studied of galaxies) is also consistent with the expectations of AC (e.g., Seigar et al. 2008a), maybe this suggests that Malin 1 has properties similar to those of normal surface brightness, bulge-dominated galaxies, of which to-date only a handful have been studied in this manner. From here on, we adopt our AC model as the fiducial model. The virial mass, M_{vir} , and concentration, c_{vir} , for the best fitting

halo model are listed in Table 1. Table 2 lists parameters of both the non-AC and AC models for comparison. Figure 2 shows the enclosed mass as a function of radius for our best-fitting AC model, separated into bulge, inner disk, outer disk and halo components.

The most interesting aspect of the best-fitting rotation curve, is the fact that it appears to be dominated by the bulge in the inner regions of Malin 1, out to a radius of ~ 7 kpc. As LSB galaxies are often referred to as being dark matter dominated at all radii, on the surface this result would suggest that Malin 1 may not be a typical LSB galaxy. However, the studies of dwarf LSB galaxies by de Blok & McGaugh (1997) and Kuzio de Naray et al. (2006, 2008) show that these galaxies may actually be baryon dominated in their very central ~ 1 kpc. By extrapolation to giant LSB galaxies it may seem plausible that these larger counterparts may also be baryon dominated out to $\sim 5 - 10$ kpc. However, a common criterion for classifying LSB galaxies is a disk central surface brightness fainter than $\mu_B = 23.0$ mag arcsec $^{-2}$ (Impey & Bothun 1997). A galaxy with a disk central surface brightness fainter than this would present a $> 4\sigma$ deviation from the distribution of disk surface brightnesses found by Freeman (1970). As a result any galaxy with a disk central surface brightness less than $\mu_B = 23.0$ mag arcsec $^{-2}$ is typically classified as an LSB. However, Barth (2007) determined a B band disk central surface brightness of $\mu_B(0) = 22.3$ mag arcsec $^{-2}$ for Malin 1. This would not classify Malin 1 as

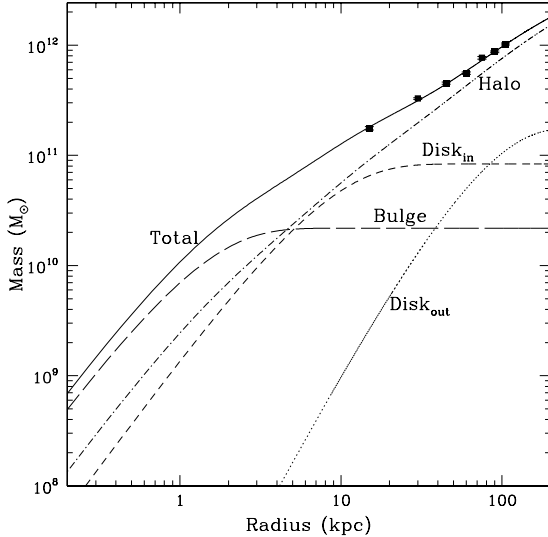


Fig. 2.— Total enclosed mass (solid line) as a function of radius for Malin 1 for the best-fitting AC model. The enclosed mass is divided into its bulge (short-dashed line), inner disk (long-dashed line), outer disk (dotted line) and dark matter halo (dot-dashed line) components. The data points correspond to the H I rotation curve data from Sancisi & Fraternali (2007) shown in the left panel of Figure 1.

an LSB galaxy, but as an intermediate surface brightness disk, if we were to use the classification system of McGaugh (1996). Taken together with our mass profile, which seems to suggest that Malin 1 is baryon dominated out to large radii, this may be revealing that Malin 1 is not as atypical as originally thought. It seems that Malin 1 has characteristics that are similar to those of SBO type galaxies, but it is also embedded in a very extended, optically faint, gas-rich outer disk beyond its normal inner disk.

Although the inner most point of the rotation curve is at 15 kpc, it would be difficult to model Malin 1 with any cosmologically motivated dark matter profile that would not be baryon dominated within ~ 5 kpc. Even a pseudo-isothermal profile (see e.g., Simon et al. 2005; Kuzio de Naray et al. 2006 for a description of the pseudo-isothermal profile) would be baryon dominated out to a similarly large radius, as such a profile tends

to provide comparatively less dark matter at small radii.

Given the lack of points within 15 kpc, it is almost impossible to determine whether a NFW model or a pseudo-isothermal model provides the best possible profile for the dark matter halo of Malin 1. The difference between these two types of dark matter halo profile are most sensitive in the very inner regions, where the NFW-type profile provides a “cuspy” inner density profile and the pseudo-isothermal profile provides a constant density core (see e.g., Simon et al. 2005). To determine which of these best describes the halo of Malin 1, we would need better sampled kinematics within the inner 15 kpc. Since more and more evidence seems to suggest that pseudo-isothermal models work better for describing the dark matter distribution in disk galaxies (e.g., Gentile et al. 2004, 2005; Shankar et al. 2006; Spano et al. 2008) it seems important better sampled spectroscopy be observed for the inner regions of Malin 1 in any future study.

Of course, the use of optical data to model the stellar parts of Malin 1 is limited. The expected stellar M/L ratio in the optical has a very large scatter (e.g., Bell & de Jong 2001; Bell et al. 2003), and ideally we would prefer to have near-infrared images of Malin 1, which would provide a more accurate stellar M/L ratio.

4. Does Malin 1 lie on the Spiral Arm Pitch Angle versus Shear relation?

4.1. Measurement of the pitch angle of Malin 1

Spiral arm pitch angles are measured using the same technique employed by Seigar et al. (2004, 2005, 2006, 2008b). A two-dimensional fast-Fourier transform technique (FFT) is used, which employs a program described by Schröder et al. (1994). Logarithmic spirals are assumed in the decomposition. The amplitude of each Fourier component is given by

$$A(m, p) = \frac{\sum_{i=1}^I \sum_{j=1}^J I_{ij}(\ln r, \theta) \exp[-i(m\theta + p \ln r)]}{\sum_{i=1}^I \sum_{j=1}^J I_{ij}(\ln r, \theta)}, \quad (2)$$

where r and θ are polar coordinates, $I(\ln r, \theta)$ is the intensity at position $(\ln r, \theta)$, m represents the number of arms or modes, and p is the vari-

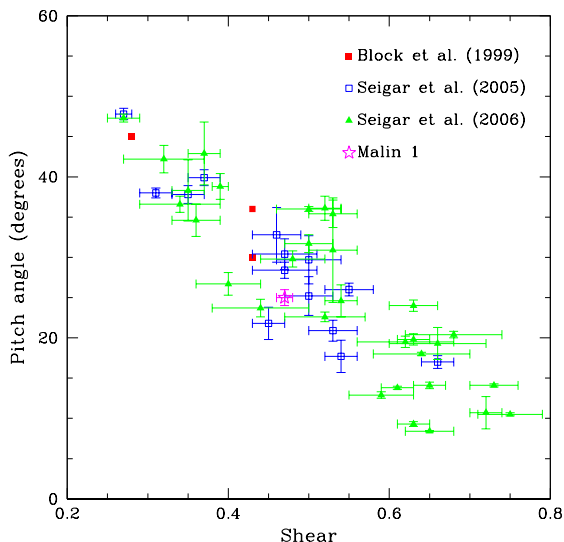


Fig. 3.— The Pitch angle versus Shear relation from Seigar et al. (2005, 2006) with Malin 1 overlaid. The red points represent data from Block et al. (1999); the blue points represent data from Seigar et al. (2005); the green points represent data from Seigar et al. (2006) and the magenta point represents Malin 1.

able associated with the pitch angle P , defined by $\tan P = -(m/p)$. We measure the pitch angle P of the $m = 2$ component. The resulting pitch angle measured using equation 2 is in radians, and this is later converted to degrees for ease of perception.

The range of radii over which the FFT was applied was selected to exclude the bulge (where there is no information about the arms) and to extend out to the outer limits of the arms in the deep R-band image of Malin 1 from Moore & Parker (2007). The radial extent of the bar was measured manually (see, e.g., Grosbol et al. 2004), and the inner radial limit applied to the FFT was chosen to be outside this radius. The physical distance was calculated using a Hubble constant $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Spergel et al. 2007) and the recessional velocity, $V_{\text{rec}} = 24750 \pm 10 \text{ km s}^{-1}$ (de Vaucouleurs et al. 1991; hereafter RC3). The pitch angle was then determined from peaks in the Fourier spectrum, as this is the most powerful method for finding periodicity in a distribution (Considère & Athanassoula 1988; Garcia-

Gomez & Athanassoula 1993). The radial range over which the Fourier analysis was performed was chosen by eye and is probably the dominant source of error in the calculation of the pitch angle, as spiral arms are only approximately logarithmic and sometimes abrupt changes can be seen in spiral arm pitch angles (e.g., Seigar & James 1998).

The image was first deprojected to face-on. Mean uncertainties of position angle and inclination as a function of inclination were discussed by Considère & Athanassoula (1988). For a galaxy with high inclination, there are clearly greater uncertainties in assigning both a position angle and an accurate inclination. These uncertainties are discussed by Block et al. (1999) and Seigar et al. (2005), who take a galaxy with low inclination ($< 30^\circ$) and one with high inclination ($> 60^\circ$) and varied the inclination angle used in the correction to face-on. They found that for the galaxy with low inclination, the measured pitch angle remained the same. However, the measured pitch angle for the galaxy with high inclination varied by 10%. Since inclination corrections are likely to be largest for galaxies with the highest inclinations, cases in which inclination is $> 60^\circ$ are taken as the worst case scenario. Since the inclination of Malin 1, $i \simeq 23^\circ$, the error in deprojecting to a face-on orientation is likely to be very low.

From the R band image of Malin 1 presented in Moore & Parker (2007), the pitch angle of their overlaid spiral is measured as $P = 25.0 \pm 1.0$.

4.2. Measurement of rotation curve shear

We use our best fit model rotation curve to the H I rotation velocities from Sancisi & Fraternali (2007) to measure the shear for Malin 1. The shear is measured using the same method used by other authors (e.g., Block et al. 1999; Seigar et al. 2004, 2005, 2006; Seigar 2005).

Rotation curve shear is defined as,

$$S = \frac{A}{\omega} = \frac{1}{2} \left(1 - \frac{R}{V} \frac{dV}{dR} \right), \quad (3)$$

where A is the first Oort constant, ω is the angular velocity, and V is the rotation velocity at a radius R . The shear depends on the shape of the rotation curve. For a rotation curve that remains flat, $S = 0.5$, for a falling rotation curve, $S > 0.5$, and for a continually rising rotation curve, $S < 0.5$.

Using equation 3 and the model rotation curve, we have calculated the shear for Malin 1 at a radius of 10 kpc (the same radius at which Seigar et al. 2005, 2006 measured their values for rotation curve shear). The dominant source of error on the measurement of shear is the rms error in the rotation curve. This is typically $< 10\%$. In order to calculate the shear, the value of dV/dR , measured in $\text{km s}^{-1} \text{ arcsec}^{-1}$, is calculated as a function of radius for the outer part of the rotation curve (i.e., past the radius of turnover and the bulge component).

Using this technique we find a rotation curve shear of Malin 1, $S = 0.47 \pm 0.01$, indicating that the rotation curve for Malin 1 is declining at this radius.

4.3. The shear versus pitch angle relation

From the spiral arm detected by Moore & Parker (2007), the pitch angle of Malin 1 is $P = 25^\circ 0 \pm 1^\circ 0$. We also find a shear of $S = 0.47 \pm 0.01$ from the H I rotation curve presented by Sancisi & Fraternali (2007). Figure 3 shows the result of plotting the pitch angle and shear of Malin 1 on the spiral arm pitch angle versus rotation curve shear relation from Seigar et al. (2005, 2006). As can be seen Malin 1 fits nicely on this relation, which was originally determined for normal spiral galaxies. This is the first LSB galaxy which has been plotted on the shear versus pitch angle relation. It now seems appropriate that these measurements be made for more LSB galaxies to see if their shear and pitch angle remain consistent with the relation for normal brightness galaxies.

5. Conclusions

We conclude that Malin 1 is not as atypical as originally thought. We highlight the fact that its B band disk central surface brightness of $\mu_B(0) = 22.3 \text{ mag arcsec}^{-2}$ as determined by Barth (2007) seems to place it in the category of intermediate brightness galaxies (McGaugh 1997). Taken together with our result here, that Malin 1 appears to be baryon dominated to ~ 10 kpc, this may suggest that Malin 1 has characteristics typical of normal galaxies. However, it still remains a very unusual galaxy, as it is also embedded in a very extended, gas-rich, outer disk. While Barth (2007) compared Malin 1 to SBO galaxies,

the discovery of spiral structure in its disk (Moore & Parker 2007) would suggest that Malin 1 may very well be of later-type than this. The break in the outer disk of Malin 1 to that of a disk with a larger scalelength is not unusual for disk galaxies (e.g., Pohlen et al. 2002; Erwin et al. 2005, 2007). Malin 1 may just exhibit an extreme case of this phenomenon.

The spiral structure and rotation curve shear of Malin 1 are both consistent with those of normal disk galaxies, and they both fall nicely on the rotation curve shear versus spiral arm pitch angle relation reported by Seigar et al. (2005, 2006). It is possible that a comparison of shear values and pitch angles for LSB galaxies reveal that they follow the same relation as normal galaxies. For this reason, in the future, we intend to make these measurements for a large sample of LSB galaxies.

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